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RESEARCH ARTICLE

Nitrogen and phosphorus retention in Danish restored wetlands

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Abstract Wetland restoration is considered an effective mitigation method for decreasing nitrogen (N) losses from agricultural land. However, when former cropland becomes rewetted, there is a risk that phosphorus (P) accumulated in soils will be released downstream. Here, we evaluate N and P retention in eight restored wetlands in Denmark monitored for 1 year using a mass balance approach. The wetlands represented different types, for instance, lakes and wet meadows, and ages (3–13 years). We also show the results from a long-term monitoring station established in 1973, located downstream a lake that was re-established in 2006. All restored wetlands removed total N (42–305 kg N ha^{-1} year^{-1}), while some wetlands acted as source of total P and others as a sink (− 2.8 to 10 kg P ha^{-1} year^{-1}). Our study confirms that restored wetlands are effective at removing N, whereas P can be released for several years after restoration.

Keywords Eutrophication · Hydraulic residence time · Nitrogen · Phosphorus · Wetland restoration

INTRODUCTION

Excess nitrogen (N) and phosphorus (P) concentrations are a subject of serious concern in many aquatic ecosystems worldwide due to the extensive negative impacts on drinking water quality and biodiversity (Smith et al. 1999; Grizzetti et al. 2012; Fowler et al. 2013; Van Meter et al. 2018). To mitigate these impacts, several environmental policies have been implemented to limit N and P losses to waterbodies in Europe [e.g. the EU Water Framework Directive (European Commission 2000)] and the rest of the world. However, in spite of these efforts, N and P pollution is likely to remain a major environmental challenge in the future as the global use of agricultural N and P fertiliser is still increasing to meet the food demand of the growing world population (Bodirsky et al. 2014; Lu and Tian 2017). Furthermore, intensification of agriculture also increases N and P losses, especially if improved management practices (e.g. buffer strips, catch crops) are not implemented (Galloway et al. 2008; Constantin et al. 2010; Roberts et al. 2012).

Wetland restoration is often presented as an efficient tool to mitigate N losses from agricultural areas to surface waters (Jansson et al. 1994; Comín et al. 1997; Mitsch and Jørgensen 2004). It generally aims at rewetting drained organic soils to create conditions favourable for denitrification, i.e. anoxia and available carbon. Denitrification is a microbial process that converts nitrate (NO_3^-) or nitrite (NO_2^-) dissolved in the water into nitrous oxide (N_2O) or dinitrogen gas (N_2) (Tiedje 1982). This natural process helps to decrease aquatic N pollution, and wetlands are therefore sometimes described as 'kidneys' of the landscape (Mitsch and Gosselink 1986). Practical restoration measures include, for example, disconnection of tile drains to raise the water table in riparian areas, re-meandering of channelised streams and re-establishment of reclaimed lakes.

Many countries have implemented wetland restoration projects with the aim to reduce N loads to surface waters (Bernhardt et al. 2005; Hoffmann and Baattrup-Pedersen 2007). Unfortunately, the full effect of these measures on nutrient retention is still unclear because most restoration projects are not, or inadequately, monitored (Bernhardt et al. 2005). Although most studies have shown that N is

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effectively retained shortly after restoration, there is large variation in N removal efficiency (Hoffmann and Baattrup-Pedersen 2007; Land et al. 2016). Several lines of evidence suggest that N removal efficiency in wetlands is connected to factors such as N load per surface area, hydraulic loading, wetland type, temperature and the wetland-to-catchment area ratio (Strand and Weisner 2013; Land et al. 2016; Vymazal 2017). Nitrate removal by denitrification and other processes might also be influenced by the age of the wetland as it takes several years for the vegetation to establish and for hydro-biogeochemical properties to be restored (Moreno-Mateos et al. 2012).

Furthermore, the long-term effect of wetland restoration on P is uncertain as newly restored areas tend to release P, especially following rewetting of former agricultural organic soils (Aldous et al. 2007; Zak and Gelbrecht 2007; Hoffmann et al. 2011). Phosphorus often accumulates in such soils as a consequence of over-fertilisation (Rowe et al. 2016) and mineralisation of soil organic matter (Zak et al. 2008). Phosphorus can be retained in soils by sorption to iron minerals, but upon rewetting the change in redox conditions from oxic to anoxic may lead to reduction of iron oxides and subsequent release of the redox sensitive iron-bound P fraction (Aldous et al. 2007). This release of P to surface waters lasts until the redox sensitive P pool in the soil is depleted and reaches an equilibrium with the overlying water, a process that may take years to decades (Zak et al. 2010). However, retention of particulate P by sedimentation and biological uptake of P are also expected to become significant processes in the restored wetlands (Reddy and DeLaune 2008; Zak et al. 2014).

Denmark was among the first countries, as early as 1998, to implement a national programme of wetland restoration aiming at reducing diffuse N losses to aquatic ecosystems. In the past, many Danish riparian areas and shallow lakes were drained to promote agricultural activities, urban development and water reclamation (Hoffmann and Baattrup-Pedersen 2007). The Danish Action Plan for the Aquatic Environment II (DAPAE-II) implemented in 1998 included the plan of restoring an area of 16 000 ha of wetlands, representing about 3.7% of the total riparian lowland area in Denmark. The aim of the restoration was to contribute to the objective of decreasing N loading to the sea by 5 600 tons. To date, about 240 wetland restoration projects have been realised, covering an area of about 19 393 ha. However, in spite of this relatively widespread use of wetland restoration in Denmark, only few projects have included subsequent monitoring to evaluate the nutrient removal efficiency. If conducted, the monitoring typically comprised only 1 year, often immediately upon restoration. Hence, the longer-term effect of restoration is unknown, particularly regarding whether the restored wetlands are acting as sources or sinks of P. Therefore, in 2015, a monitoring programme was launched in Denmark to evaluate the effect of wetland restoration on N and P removal.

Here, we present the first results of the 2015 programme for eight sites representing different wetland types of diverse restoration age, monitored during the year of 2015. We hypothesised that N and P retention per surface area of wetland is largely dependent on the nutrient loads applied and on the wetland-to-catchment area ratio. We also hypothesised that N and P retention increases with wetland age with an increasing denitrification capacity and depletion of the redox sensitive P pool. To test these hypotheses, we included in our analyses a number of previously monitored Danish restored wetlands (15 for N, 10 for P). In addition, to complement our analyses, we present the results from a long-term monitoring station (in use since 1973) located downstream a shallow lake re-established in 2006. We discuss the implications of our findings regarding N and P retention, provide suggestions for improving the monitoring and design of restored wetlands and finally give some perspectives on the impact of wetland restoration on greenhouse gas (GHG) emissions.

MATERIALS AND METHODS

Restored wetlands monitored in 2015

Eight restored Danish wetlands were monitored from December 2014 to January 2016 in order to establish annual mass balances for water, N and P. Six sites were located in Jutland (Aarslev Engsø, Grøngrøft, Lyngbygaards å, Sandskær, Tim Enge, Vilsted lake), one on the island of Funen (Geddebækken) and one on the island of Langeland (Snaremose sø) (Fig. 1). The monitored wetlands were all restored between 2003 and 2012. The design of the different projects is shown in Fig. 1. The restored wetlands comprise both shallow lakes and fens located in catchments with agriculture as the main land use ($\geq$ 48%; Table 1). The agricultural land was generally under crop rotation, mostly for production of cereals. The restored wetland areas ranged in size from 5.8 to 913 ha, while the wetland-to-catchment area ratio varied from 0.7 to 9.5% (Table 1). The catchment soil types are presented in Table 1. The total precipitation at the sites in 2015 ranged from 791 to 1088 mm (Table 1 and Fig. S1) and the average air temperature was 8.8–9.8 °C (Danish Meteorological Institute). The year 2015 was a rather wet year compared with the average precipitation in Denmark during the period 2006–2015 (792 mm), while the temperature was close to the average (8.9 °C, period 2006–2015; Danish Meteorological Institute).

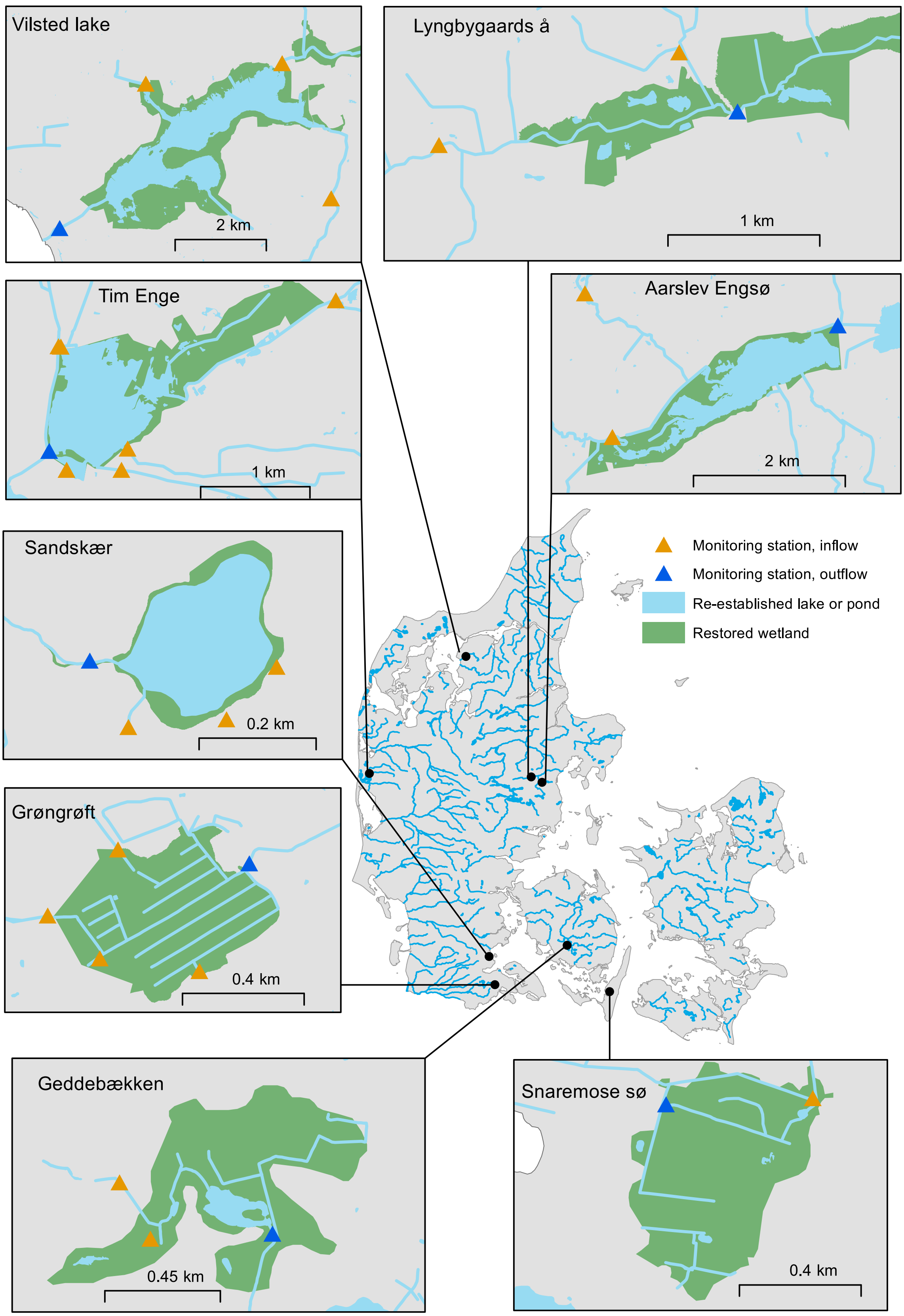

Fig. 1 Map showing the eight restored wetlands monitored during the year 2015

Table 1 Characteristics of the restored wetlands monitored in 2015

Site	Latitude and longitude (°)		Area type	Catchment area (ha)	Restored wetland area (ha)	Lake area (ha)	Wetland-to-catchment area ratio (%)	Non-monitored area		Year of restoration	Agriculture (%)	Catchment soil type			Precipitation 2015 (mm)	Average temperature 2015 (°C)
								(ha)	(%)			Sand	Clay	Peat		
Aarslev Engsø	56.140	10.071	Shallow lake and wet meadow	27 134	215	117	0.8	1817	7	2003	60	43	54	3	897	8.9
Geddebækken	55.172	10.297	Ponds and wet and dry meadow	229	20	3	8.7	44	19	2003	76	87	0	13	841	9.6
Grøngrøft	54.947	9.550	Fen	245	25.4	–	10.4	50	20	2012	83	0	82	18	1088	9.6
Lyngbygaards å	56.167	9.913	Riparian fen and wet meadow	5721	40	–	0.7	781	14	2007	62	60	37	3	914	8.8
Sandskær	55.113	9.491	Shallow lake and wet meadow	114	5.8	4.5	5.1	27	24	2011	48	92	5	3	986	9.4
Snaremose Sø	54.894	10.727	Fen and reed swamp	565	31	–	5.5	185	33	2002	87	9	91	0	791	9.8
Tim Enge	56.193	8.229	Shallow lake and wet meadow	10 059	152	103	1.5	461	5	2007	58	79	5	16	1024	9.4
Vilsted lake	56.885	9.262	Shallow lake, wet meadow and reed swamp	9588	913	450	9.5	2570	27	2006	71	83	0	17	945	8.7

Description of the mass balance approach

The objective of the monitoring programme was to estimate the retention of N and P in the restored wetlands. For this purpose, a mass balance of water and nutrients (N, P) entering and leaving the restored wetland was established. The monitoring programme included daily discharge estimates at the main inlet(s) and outlet of the restored areas (see Fig. 1). Discharge at the inflow was estimated based on discharge versus stage (Q/h) relationships or discharge versus discharge (Q/Q) relationships with the downstream station at the outlet of the wetland when a gauging station from the national monitoring programme was present. To establish the relationships, the discharge was measured in the inlets at every sampling event (i.e. once a month) and a logger was placed to continuously record the water stage. All the monitored sites had only one outflow. It was not possible to measure all the sources of water entering the wetland, especially groundwater, smaller ditches and drains, and for ungauged areas (i.e. areas where the discharge was not measured), discharge was calculated as the specific discharge at the inlets of the wetland multiplied by the surface of the ungauged area minus the restored area. The size of the ungauged areas varied between 7 and 33% of the total catchment area discharging to the restored wetlands (Table 1). We accounted for precipitation and evapotranspiration in the restored areas using precipitation and potential evapotranspiration data for the corresponding climatic grid cells provided by the Danish Meteorological Institute ($10 \times 10\,km^2$ grid for precipitation and $20 \times 20\,km^2$ for potential evapotranspiration). We assumed that the wetlands never dried out, i.e. that the evapotranspiration in the wetlands matched the potential evapotranspiration. In fact, surface water inlets never stopped to flow in seven of the eight wetlands. Only at Snaremose sø, the surface water inlets dried out in summer, whereas water kept flowing at the outlet.

Grab samples at the main inlets and outlets were taken monthly and analysed for nutrients (NO_3^-, TN, PO_4^{3-} and TP). Inlets and outlets at a given site were sampled on the same day. A few smaller ditches and tile drains entering some of the restored wetlands were also monitored for nutrients. Discharge was not measured at these smaller additional inlets. The contributions of nutrients from ungauged areas were estimated using the area-specific nutrient load at the main inlets (or additional inlets when available) multiplied by the surface area of the ungauged upland minus the area of the restored wetland. We made the assumption that ungauged areas had similar land use as the gauged areas so that the area-specific nutrient export from the ungauged areas was similar to the export from the inlets.

The monthly nutrient transport was calculated as the flow-weighted concentration using interpolated daily flows and nutrient concentrations. It has been shown that the use of linear interpolation is the best and most reproducible method (per site and year) for Danish streams when using monthly grab sampling (Kronvang and Bruhn 1996). The nutrient removal (in kg N or P) at each wetland was calculated as the difference between the sum of the nutrient transport at all inlets and ungauged areas minus the nutrient transport at the outlet. Hence, positive values indicated nutrient retention, while negative values indicated release. To calculate the area-based removal efficiency, the nutrient removal was divided by the whole restored wetland area (Table 1). However, at Geddebækken, only the 3 ha covered by lake were included in the calculation of nutrient removal efficiency because the rest of the project area (17 ha) was rather dry and accordingly did not offer conditions suitable for denitrification. At Tim Enge, the water samples collected in July had unusually high TN and TP concentrations due to a ~ 3-day resuspension event in the lake caused by strong winds. Instead of linear interpolation, we therefore used piecewise constant interpolation based on the values measured in June and August and then included the July event in our daily TN and TP time-series.

Long-term nutrient transport at restored Vilsted lake

Vilsted lake was re-established in 2006. The lake was part of the sites monitored in 2015 for which a mass balance was set up. However, a monitoring station placed in the middle of the project area had measured monthly nutrient concentrations and daily discharge since 1973, i.e. before the re-establishment of the lake, allowing observation of potential changes in nutrient transport over time and, not least, after the re-establishment of the lake. Before the re-establishment, in January 2005, this station was closed and replaced by a new located 3.5 km further downstream, but for a 17-month overlap period discharge and nutrient monitoring was undertaken at both stations, enabling us to check for potential differences and assess the comparability of the data from the two stations. Furthermore, we used the data from the two stations to compare the nutrient transport before and after lake re-establishment.

Water chemistry

All nutrient analyses for the wetlands monitored in 2015 followed Danish/EU standards: for TN (DS/EN ISO 11905 2004); TP (DS/EN ISO 6878 2004); NO_3^- (Method 4500-NO_3 Nitrogen (Nitrate) 2017) and PO_4^{3-} (Method 4500-P Phosphorus 2017) at the ISO-accredited laboratory Eurofins, Denmark. The same methods and laboratory were used for the long-term monitoring at Vilsted lake from 2002 to 2016 except that NH_4^+ was included in the analyses (Method 4500-NH_3 nitrogen (Ammonia) 2017). Before 2002, nutrient analyses were made according to Danish standards at LMK Ålborg laboratory.

Statistical methods

To assess factors (e.g. nutrient load, wetland age) influencing TP and TN removal in restored wetlands, we considered in our analyses several studies establishing nutrient balances in Danish restored wetlands, including those of Hoffmann et al. (2006), Hoffmann and Baattrup-Pedersen (2007), Hoffmann et al. (2011) and Hoffmann et al. (2012), who estimated yearly TN removal in 15 wetlands and TP removal at ten wetland sites. The methods used in these studies were comparable to ours, i.e. mass balance approaches with monthly nutrient sampling. Using the results from the eight wetlands monitored in 2015 and the wetlands previously monitored, linear regressions were applied to the full data set ($n = 23$ for N and $n = 18$ for P) to model the relationships between TN and TP percentage removal using one of the following explanatory variables: TN or TP load, wetland age and the wetland-to-catchment area ratio. All numeric explanatory variables were transformed using natural logarithms to meet the assumption of normality. The correlation coefficient R-squared (R^2) was used to evaluate the goodness of fit of the relationships.

We employed paired t-tests to compare the nutrient measurements from the two monitoring stations at Vilsted lake during the overlap period to assess the validity of the comparison between the old and the new station.

All tests were performed using the R software version 3.4.4 (R Development Core Team 2018).

RESULTS

Water and nutrient balance for the eight wetlands monitored in 2015

To estimate nutrient retention in restored wetlands using a mass balance approach, it is crucial to check that the sum of the inflowing water matches well with the outflowing water. The yearly water balance in the wetlands showed that the difference between inflow and outflow varied from − 7.9 to 6.9% (Table 2). Specifically, 7.9% of the inflowing water was lost in Snaremose sø, while there was a 6.9% gain of water in Tim Enge (Fig. S2).

Flow-weighted influent concentrations revealed large differences among the wetlands (Table S1). The highest average yearly concentration of TN, 9.1 mg N L^{-1}, was found in Geddebækken and the lowest, 2.6 mg N L^{-1}, in

Table 2 Water and nutrient balances in the restored wetlands. The water balance represents the difference in water discharge between the inlet and outlet; negative values indicate loss of water, positive values gain of water. Nutrient removal is shown as the removal per surface area of restored wetland per year (in kg ha^{-1} year^{-1}) and as a percentage of the total nutrient transport to the wetland. Negative values indicate wetland nutrient release

Site	Water balance (diff inflow-outflow) (%)	TN removal		NO_3^- removal		TP removal		PO_4^{3-} removal	
		kg ha^{-1} year^{-1}	%	kg ha^{-1} year^{-1}	%	kg ha^{-1} year^{-1}	%	kg ha^{-1} year^{-1}	%
Aarslev Engsø	− 1.5	261	15	299	21	10.3	18	13.2	47
Geddebækken	5.3	42	2	56	3	− 2.8	− 12	6.3	59
Grøngrøft	− 2.6	98	40	88	49	0.0	0	− 1.1	− 16
Lyngbygaards å	− 5.7	308	12	304	13	6.4	13	3.2	20
Sandskær	1.3	176	42	203	54	− 0.6	− 5	− 2.2	− 36
Snaremose sø	− 7.9	191	39	190	42	− 0.6	− 10	− 0.5	− 11
Tim Enge	6.9	70	5	34	4	10.0	17	1.4	12
Vilsted lake	6.7	70	23	112	41	− 1.4	− 29	2.1	65

Tim Enge. All sites exhibited lower TN concentrations in the effluent water than in the influent water. A similar trend was observed for NO_3^-. Inlet TP concentrations ranged from 0.09 to 0.24 mg P L^{-1} and outlet concentrations between 0.08 and 0.25 mg P L^{-1}. Influent PO_4^{3-} concentrations varied between 0.02 and 0.12 mg P L^{-1} and effluent concentrations between 0.02 and 0.15 mg P L^{-1}. There was no consistent trend for TP and PO_4^{3-}, some sites acting as P sinks and others as P sources.

The yearly TN balance showed that all wetlands removed TN at rates ranging between 42 and 308 kg N ha^{-1} year^{-1} (Table 2). The highest removal rate (308 kg N ha^{-1} year^{-1}) was measured at Lyngbygaards å, constituting 12% of the TN load, and the lowest (21 kg N ha^{-1} year^{-1}) at Geddebækken, representing 2% of the TN load. The highest removal efficiency was measured at Sandskær where 42% of the TN was removed (Table 2). Noteworthy, the NO_3^- removal was higher than the TN removal at Aarslev Engsø, Geddebækken, Sandskær and Vilsted lake. The yearly TP balance revealed that only three wetlands (Aarslev Engsø, Lyngbygaards å and Tim Enge) acted as TP sinks, while all the others were TP sources. The retention was 10 kg P ha^{-1} year^{-1} at Aarslev Engsø, 6.4 kg P ha^{-1} year^{-1} at Lyngbygaards å and 10 kg P ha^{-1} year^{-1} at Tim Enge, representing 18, 13 and 17% of the TP load, respectively. At the other sites, the release was less than 1.5 kg P ha^{-1} year^{-1}. Phosphate was retained at Aarslev Engsø, Lyngbygaards å, Geddebækken, Tim Enge and Vilsted lake (Table 2); the maximum yearly PO_4^{3-} removal being 13 kg P ha^{-1} year^{-1} at Aarslev Engsø and the maximum retention percentage of the total PO_4^{3-} load being 60% at Geddebækken.

Total nitrogen and NO_3^- removal exhibited similar seasonal variations with the highest removal efficiency occurring during the warmest months of the year (May–September) (see Figs. 2a, b and S3, S4). There was no clear seasonal pattern in the retention of TP and PO_4^{3-}, although there was higher variability between the sites during the summer months (Figs. 2b, c and S4, S5).

Factors influencing total nitrogen and total phosphorus retention

Combining our data set with previously published data on nutrient removal in Danish restored wetlands showed that the TN removal was 150 ± 87 kg N ha^{-1} year^{-1} (mean ± SD) while the TP removal was 1.6 ± 4 kg P ha^{-1} year^{-1} (Table S2). The relationship between the TN load (in kg N ha^{-1} year^{-1}) and the percentage TN removal was significant (R^2 = 0.55, $p < 0.001$), showing that the greater the load, the lower the removal efficiency (Fig. 3a). Another significant relationship (R^2 = 0.25, $p < 0.01$) emerged between TN removal and the wetland-to-catchment area ratio (Fig. 3b). TN removal seemed to increase when the ratio increased, i.e. when the size of the wetland increases relative to the size of the catchment. Wetland age was not significantly associated with TN removal (R^2 = 0.08, p = 0.11, n = 25). The relationship between TP retention and TP load appeared significant (R^2 = 0.23, p = 0.03, n = 18), but a single point with a TP retention of − 127% (i.e. release of TP) had a strong influence on the relationship. When this point was removed, the relationship became insignificant (R^2 = 0.09, p = 0.12, n = 17). TP retention seemed not to be affected by either TP load (R^2 = 0.06, p = 0.16, n = 18) or the wetland-to-catchment area ratio (R^2 = − 0.03, p = 0.48, n = 18), or by the age of the wetland (R^2 = 0.05, p = 0.19, n = 18).

Long-term monitoring at re-established Vilsted lake

To ensure a valid comparison between the old and the new monitoring station at Vilsted lake, the discharge measured

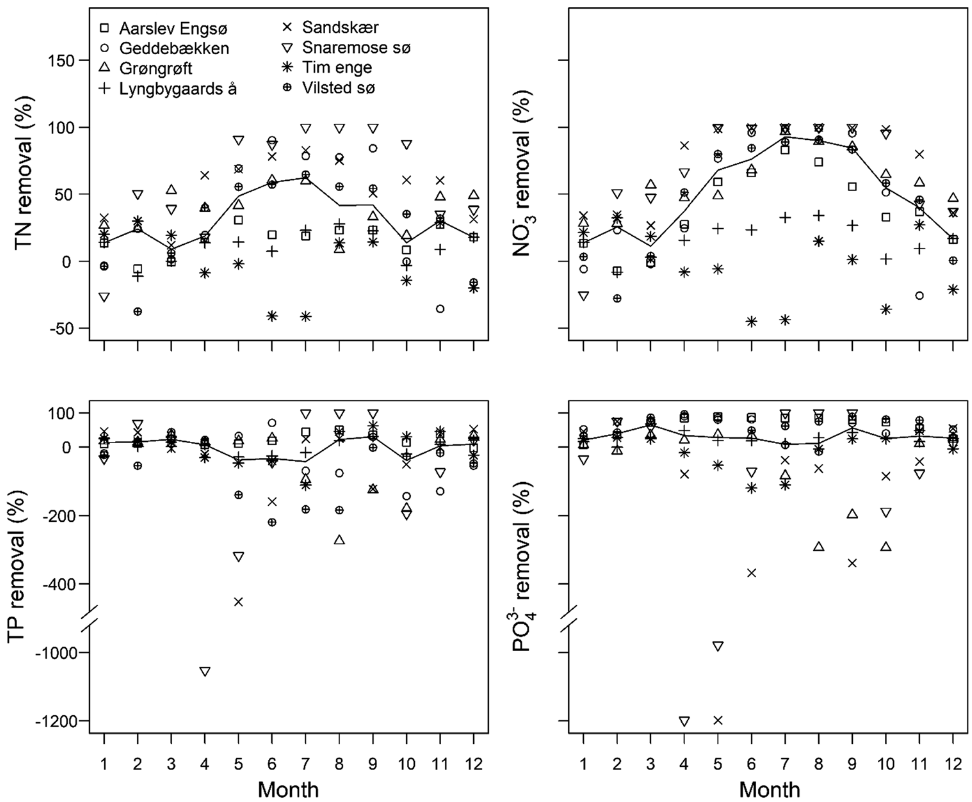

Fig. 2 Nutrient removal at the eight wetlands restored in 2015 expressed as percentages of the monthly total transport of TN, NO_3^-, TP and PO_4^{3-}. Negative percentage indicates release of nutrients from the wetland. The black line represents the median of the measurements

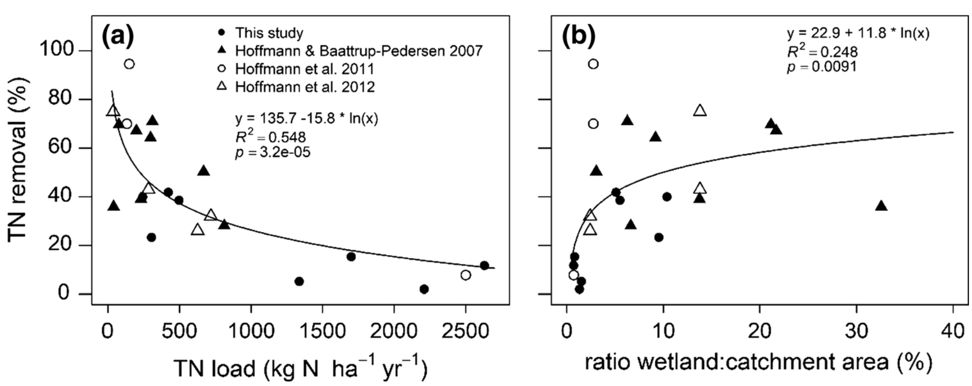

Fig. 3 **a** Total nitrogen removal (%) versus TN load per surface area of restored wetland. **b** Total nitrogen removal (%) versus the restored wetland-to-catchment area ratio (%). Number of studies, $n = 23$

at the two stations during the overlap period (January 2005 to May 2006) was compared using linear regressions. The discharge at the lower (new) station was 1.4 times higher than at the old station ($R^2 = 0.93$, $p < 0.0001$, $n = 508$), but the data for the period January to March 2005 fitted poorly with the regression line, possibly because the Q/h relationship was not reliable when the monitoring started at the new station (Fig. S7). When excluding the data from January to March 2005, the relationship improved ($R^2 = 0.99$, $p < 0.001$, $n = 418$), and according to the new regression the discharge at the new station was 1.2 higher than the discharge at the old station. The increase in discharge matches well with the increase in catchment area from 82 km^2 at the old station to 96 km^2 at the new station.

The concentrations of NH_4^+, TP and PO_4^{3-} measured at the old and the new station during the overlap period did not differ significantly (paired t test, $p > 0.05$), whereas TN and NO_3^- exhibited significant differences. Indeed, the mean concentrations of TN and NO_3^- measured at the old (upstream) station were slightly lower (− 0.22 and

− 0.46 mg N L^{-1}, corresponding to − 2.6 and -8.9%) than the concentrations measured at the new (downstream) station during the overlap period (Table S3).

The yearly nutrient transport at the new station downstream of Vilsted lake revealed marked changes following the re-establishment of the lake in 2006. The yearly load of TN and NO_3^- decreased markedly after 2006 despite a similar or slightly higher water discharge than in 1985–2005 (Fig. 4). The NH_4^+ load did not change notably after 2006, although a few "peak-years" could be observed during the period 2006–2017. The TP load increased markedly after the restoration, especially in the first 3 years following the establishment of the lake. Similarly, the PO_4^{3-} load showed a clear increase after the restoration but decreased again to pre-restoration levels after 2008 and to even lower levels after 2015.

DISCUSSION

Nutrient retention in restored wetlands

The calculated nutrient retention in eight restored wetlands monitored in 2015 confirmed the efficacy of wetlands in removing N pollution from agricultural runoff. The range of N retention measured in the present study (42–308 kg N ha^{-1} wetland $year^{-1}$) was comparable with that of monitored restored or natural wetlands in the temperate zone (Jordan et al. 2003; Hoffmann and Baattrup-Pedersen 2007; Land et al. 2016). Considering the fact that the mean export of N leached from agricultural areas to Danish streams is estimated as ∼ 4–14 kg N ha^{-1} agricultural land $year^{-1}$ (Blicher-Mathiesen et al. 2018), our results confirm that wetlands can help mitigating N losses from croplands. At national scale, assuming a mean removal of 150 kg N ha^{-1} $year^{-1}$, the total area of restored wetland (∼ 19 000 ha) would remove about 2850 tons N $year^{-1}$. Although this result is encouraging, to reach the initial objective of 5600 tons N $year^{-1}$ set at the start of the DAPAE-II would require a doubling of the area of restored wetland.

The relatively low removal rate at Geddebækken (2% of the total load) might be explained by the circumstance that only a small part (∼ 3 ha) of the restored area was wet and offered conditions favourable for denitrification. Also, the water balance at Geddebækken showed a much higher water mass at the outflow than at the inflow in November and December (Fig. S1). This might have affected the nutrient balance, i.e. the nutrient transport to the wetland was probably underestimated as, generally, a high amount of N and P is transported during these 2 months because of a higher water discharge during November to April (Thodsen 2007).

Nitrate removal was higher than TN removal in some of the restored wetlands, especially at re-established lakes. It is likely that the biological N uptake in these restored areas was high and that NO_3^- was converted into organic-N that was later released when plant or algae decayed or were flushed out of the wetland. As NH_4^+ was not measured, we cannot exclude the possibility that some of the NO_3^- was either converted to NH_4^+ or that NH_4^+ was formed by mineralisation of organic matter in organic-rich wetland soils (Davidsson and Ståhl 2000). Previous research has not found any clear pattern on NH_4^+ retention as restored wetlands can either act as a source or a sink for NH_4^+ (Hoffmann et al. 2011). However, generally NO_3^- constituted most of the total N content in Danish surface water (Kronvang et al. 2005).

Our analysis of a data set of 23 Danish restored wetlands showed that as the yearly TN load per wetland surface area increases, the percentage removal efficiency decreases significantly. This relationship was expected as a higher N load usually implies a lower hydraulic residence time (Hill 1996). In accordance with this, it also appeared that the larger the size of the wetland relative to catchment area, the greater the TN removal. However, the percentage removal varied greatly even at comparable levels of TN load or wetland size. Some of the observed variation can probably be attributed to differences in the local geomorphic setting (e.g. soil type), hydraulic residence time and wetland type (Fisher and Acreman 2004; Land et al. 2016). Indeed, the design of the restored wetlands differed greatly among projects and often combined several features such as pond, lake, fen and wet meadow. In spite of these differences in design, our simple linear models explained up to 55% of the total variance in the yearly TN removal efficiency. The relationships between TN load and wetland size and TN percentage removal may be used to help dimensioning wetlands and ensure that the project will fulfil the N removal objectives.

Regarding P, the results from the mass balances among the restored wetlands were not consistent, some wetlands acting as sources of P and others as sinks. Other studies have also reported retention or release of P following wetland restoration (Hoffmann et al. 2009; Land et al. 2016). Contrary to TN, the TP load to the wetlands or wetland size did not have a significant effect on TP retention. Previous research has shown that the extent and duration of the P release are connected to the P sorption capacity in restored soils, the quantity of mobile P forms accumulated in drained soils and redox conditions (Zak et al. 2008). At Geddebækken, Sandskær and Vilsted lake, PO_4^{3-} seemed to be temporarily immobilised by biological uptake and also retained by other processes than sorption as these lakes acted as sinks of PO_4^{3-}, whereas they were weaker sinks or even sources of TP. This suggests that

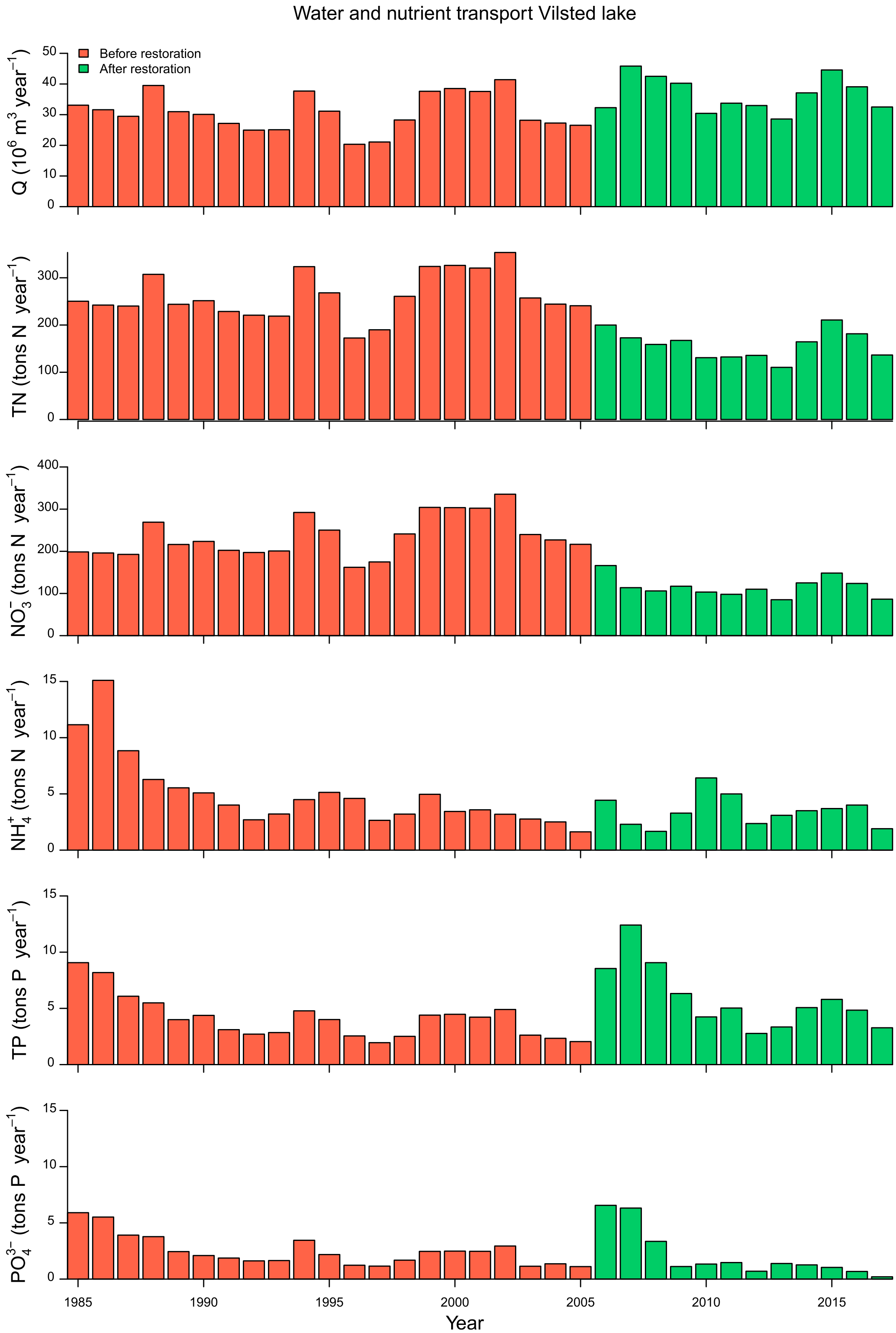

Fig. 4 Water and nutrient transport per year at the monitoring station downstream Vilsted lake. Data are available from 1973, but for the purpose of conciseness only the period 1985-2017 is shown. The green bars represent the period after lake re-establishment

PO_4^{3-} is converted to organic forms of P, probably by biological uptake by plants and/or algae, and this conversion might provide opportunities for management, for instance, harvesting of the vegetation to mitigate P losses (Zak et al. 2014).

Long-term monitoring of Vilsted lake

We took advantage of the long-term monitoring of Vilsted lake to assess the effect of the re-established lake on the yearly variation in nutrient transport. Contrary to the mass balance approach, the results reflect the export of nutrients from the whole catchment. Thus, they do not solely include the effect of the re-establishment of the lake but also any changes in the catchment, for instance, changes in land-use and agricultural practices (e.g. lower fertiliser use). We detected a clear shift in nutrient transport following the re-establishment of the lake in 2006 as the TN and NO_3^- transport decreased markedly after the re-establishment and seemed to decrease even further in the subsequent years. It is assumed that most of the decrease in TN and NO_3^- transport is due to denitrification in the lake, but climatic variations and land-use changes in the catchment are also likely to alter the nutrient transport. Indeed, after the re-establishment of Vilsted lake, about 450 ha of arable land in crop rotation have been converted to unfertilised permanent grassland in the areas surrounding the lake and 7 km ditches and several drain systems have been disconnected in the catchment. As the new monitoring station was located further downstream and received more water ($\sim$ 20%) than the old station, the nutrient transport measured here is probably slightly higher than it would have been at the old station.

In contrast to TN and NO_3^-, the TP and PO_4^{3-} transport clearly increased after the re-establishment of the lake and was especially high in the first 3 years following the restoration. The increase was probably due to change in redox conditions in the newly flooded soil that turned from oxic to anoxic, thereby releasing P bound to redox sensitive metal oxides, particularly iron oxyhydroxides (Jensen et al. 1992). Three years after re-establishment of the lake, a sharp decrease in PO_4^{3-} transport was observed and the transport of PO_4^{3-} was only 203 kg in 2017 compared with 6600 kg in 2006 immediately upon the re-establishment. After 2009, the TP transport remained relatively high, around 5000 kg P year^{-1}, which could indicate a conversion of inorganic-P to organic forms of P in the lake. These results regarding both N and P are consistent with the nutrient mass balance obtained for 2015 in Vilsted lake as part of the wetland monitoring programme. It supports the idea that P is converted from inorganic to organic forms and that a substantial amount of N was retained. Nevertheless, 9 years after the re-establishment, the lake still functioned as a source of P.

Effect of wetland age

According to our results, the age of the restored wetlands appeared not to have any significance for TN removal. Thus, N removal processes were seemingly quickly restored. At the long-term monitoring station at Vilsted lake, a drop in N transport was detectable even in the 1st year after the restoration, and although the N transport at the monitoring station downstream the lake seemed to decrease in the years following the restoration, it is not clear whether this should be ascribed to an enhanced denitrification capacity, a change in agricultural practices in the catchment or climatic conditions—or a combination of the three. We found different N removal rates at Lyngbygaards å, 308 kg N ha^{-1} year^{-1} in 2015 compared with a higher rate the 1st year after restoration (2008) when retention was 195 kg N ha^{-1} year^{-1} (Hoffmann et al. 2011). This difference could not be explained by differences in N transport (105 tons in 2015 vs. 100 tons in 2008) and suggests that the denitrification capacity increased at this site with wetland age; for instance, accumulation of fresh and more labile organic carbon pools might have occurred (Hernandez and Mitsch 2007). On the other hand, previous mass balances obtained for Snaremose sø in 2003 and Geddebækken in 2004 showed that TN removal was higher in 2004 than in 2015 despite lower N transport.

Contrary to N, the results from the eight wetlands monitored in 2015 showed that many restored sites acted as sources of P and that the P release may last for several years or even decades (Zak et al. 2008). We did not find a link between wetland age and P release using data from 18 Danish restored wetlands. However, it is challenging to discover clear trends in P release over time in a data set combining different restoration designs and wetlands with contrasting P pools and disparate soil properties. For instance, when contemplating the long-term data from the Vilsted monitoring station, P transport showed a marked increase immediately upon the lake restoration, followed by a decrease over time, while other wetlands, restored as early as in 2002 or 2003, still functioned as a P source 12–13 years after restoration. Therefore, assessment of the full effect of wetland restoration on P seems to require several decades of monitoring in order to estimate the point when restored wetlands shift from acting as a P source to acting as a P sink.

Uncertainties of nutrient estimates and opportunities for improvement

The monitoring of restored wetlands faces several challenges that need to be addressed to obtain a reliable assessment of their effect on N and P retention. Only few restoration projects involve monitoring; particularly monitoring *before* the restoration is rarely included although it can provide valuable information assisting in assessing the actual effects of the restoration. The establishment of a reliable water balance is challenging because it is difficult to accurately measure all sources of water, especially in catchments with a substantial groundwater gain or loss. For example, unaccounted-for groundwater inputs might be the reason for the substantial difference in water discharge observed in the summer months at Tim Enge. Furthermore, the delineation of actual hydrographic catchments based on topography might be uncertain and requires information on geological settings and the presence of artificial drainage, especially in lowland areas. Characterisation of the restored area that is actually active and impacts the N and P retention processes may also be difficult. For example, at Geddebækken, we observed that the riparian areas were rather dry and therefore assumed that only the lake had a substantial effect on the nutrient processes. Long-term monitoring is clearly needed to evaluate the lasting effect of wetland restoration, especially regarding P as most wetlands tend to release P following restoration of agricultural land. Phosphorus, especially particulate P (PP), is often transported during peak events and grab sampling therefore tends to underestimate TP (Cassidy and Jordan 2011; Audet et al. 2014). Consequently, accurate quantification of the P release might not be obtained using monthly grab sampling as done in our study. Since the wetland will probably trap some of the particles and buffer the peak concentrations, this uncertainty in the quantification of the P transport might be especially problematic at the inflow of the wetland where P dynamics are expected to be higher than at the outflow. In this respect, use of continuous methods to monitor the nutrient transport at inflows and outflows, such as flow proportional sampling or high-frequency sensors, is recommended to better constrain estimates of nutrient retention, particularly regarding P (van Geer et al. 2016).

Perspectives on wetland restoration

Wetland restoration affects a wide range of ecosystem services (Moreno-Mateos et al. 2012), and while the provision of habitats for flora and fauna is considered beneficial, the potential detrimental release of GHG is another aspect to consider in wetland restoration projects. Many wetland restoration projects aim at promoting denitrification to remove inorganic nitrogen present in the water. Although N_2 is generally the main product of denitrification, a fraction of the N can be released as N_2O, a GHG with a global warming potential about 300 times higher than that of carbon dioxide (CO_2) (IPCC 2013). Furthermore, wetlands are also a potentially strong source of release of the GHG methane (CH_4) (Ciais et al. 2014). A study comparing GHG emissions before and after restoration of a riparian wetland in Denmark showed that the marked increase in CH_4 emissions due to rewetting of the soil was compensated for by lower CO_2 emissions (Audet et al. 2013). The same study showed that N_2O emissions remained relatively high the year after the restoration although it was speculated that it would decrease with the cease of fertilisation in the areas after restoration (Audet et al. 2013). Nevertheless, it is important to carefully evaluate the effects of wetland restoration projects by including a survey of potential ecosystem services (e.g. N removal, habitat provision) and disservices (e.g. P release, GHG emissions) in restored wetlands monitoring programmes (Verhoeven et al. 2006; Verhoeven 2014).

CONCLUSIONS

Our results confirmed that wetland restoration is an efficient way to remove N from the aquatic environment. We demonstrated that variation in N removal efficiency is connected to the N load to the wetland and to wetland size. Regarding P, our study confirmed that P loss may occur upon rewetting of the soil, and the duration of this P release may last from years to decades. The risk of P release should be carefully assessed when implementing wetland restoration measures to avoid detrimental consequences for P-limited ecosystems. Furthermore, long-term monitoring using continuous sampling methods would be beneficial to reliably characterise P retention or release in restored wetlands.

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